1-2014

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Recommended Citation
Chakravorty, Satya S. "Back In Service." Quality Progress 47.1 (2014): 38-45.

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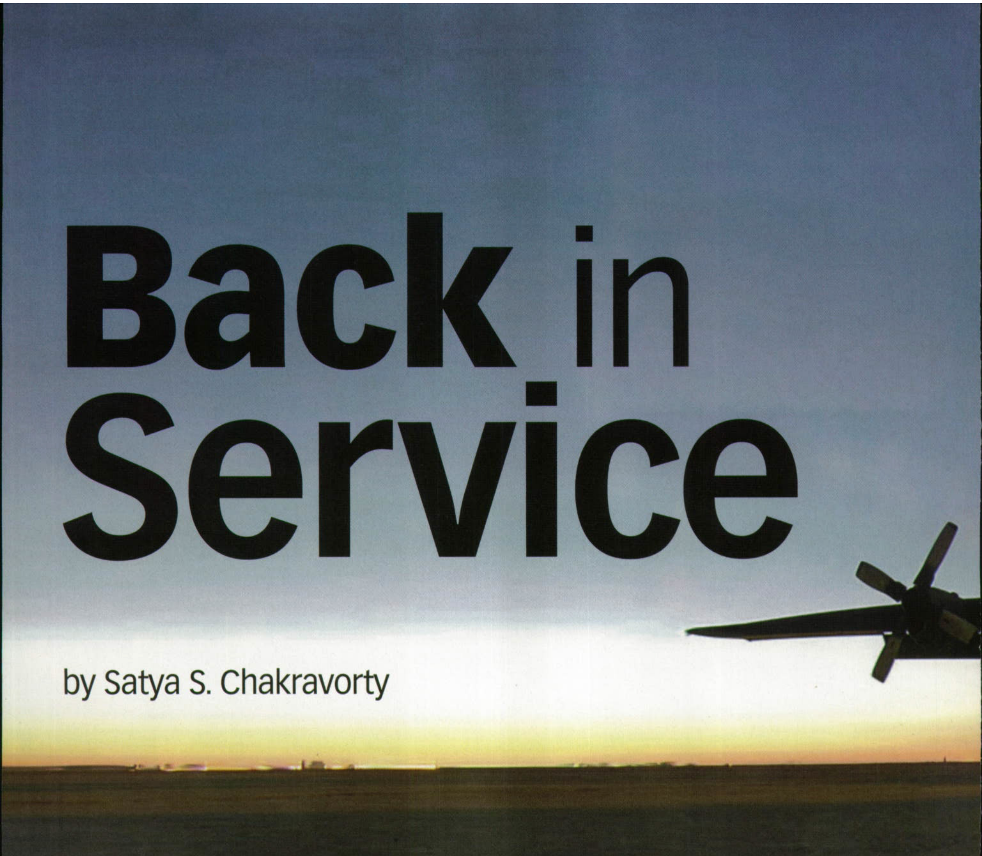
Chakravorty, Satya S
Quality Progress; Jan 2014; 47, 1; ProQuest Central
pg. 38



Back in Service

by Satya S. Chakravorty

In 50 Words Or Less

- The heavily used U.S. Air Force's C-130 Hercules requires regular maintenance to continue flying wartime and peace missions.
- One team at a military facility mixed and prioritized several quality improvement methods to retool how it repairs and restores this aircraft.
- Improvements reduced defects by 84% and saved nearly $1.5 million.

MACHINES HAVE EVOLVED from prehistoric tools to sophisticated 21st century devices. Man has been and always will be fascinated by machines and will continue to dream about building something that does what everyone thinks is impossible.

During the Renaissance, Leonardo Da Vinci designed a multitude of devices, including parachutes, and studied the flight of birds and their structure. He also romanticized concepts of flying machines in beautiful drawings.

In the late 1800s, science fiction novelist H.G. Wells wrote about the concept of time travel in *The Time Machine*. He described a vehicle that "allows an operator to

Team prioritizes quality methods to retool how it maintains, repairs and keeps the C-130 Hercules flying

travel purposefully and selectively."[1]

Throughout the years, machines have become synonymous with devices that not only facilitate new outcomes, but also produce exceptional results.

Fast forward to today. Man continues to dream and to advance the concepts of flying machines, and build aircraft that are bigger and better than ever before. One such machine is the C-130 Hercules.

One team at a military facility in central Georgia brought together several quality concepts and methods to retool the way it repairs, maintains and keeps this large transport aircraft—one of the most heavily used flying machines in the U.S. Air Force—in service.

In doing so, the aircraft's programmed depot maintenance (PDM) team produced exceptional results at Warner Robins Air Logistics Complex (WR-ALC) in Warner Robins, GA. From its efforts, in fact, the C-130 PDM team received the prestigious 2012 Secretary of Defense honor known as the Robert T. Mason Award for Maintenance Excellence. Consider this:

- The C-130 PDM team dramatically improved its due date performance from 43.86% in 2010 to 98.41% in 2012. At the same time, C-130 PDM team reduced its work in process (WIP) by 68.63%, from 51 to 16 aircrafts, putting 35 additional aircraft back in service as U.S. warfighters.
- The C-130 PDM team's flow days—the time it takes for the grounded aircraft to progress through the maintenance stages—were reduced by 32.4%, from 102 to 40 days, yielding an average monthly savings of $1.47 million and resulting in lower costs (see Table 1).

In concert with these notable achievements, the C-130 PDM team kept an intense focus on product quality and compliance, resulting in an 84% reduction in accepted customer reported defects. Throughput attained a sustained increase of 30% against the 2010 baseline, increasing output from one aircraft per week to 1.3 aircraft per week.

After a strategy was developed and implemented, the C-130 leadership focused on execution to produce results. Leaders prioritized improvement methods (for example, theory of constraints (TOC), lean and Six Sigma) using a deceptively unpretentious "squiggly line" or a damped sine wave (see Figure 1).

In physics, damping is an effect that reduces the amplitude of oscillations over time. The theory of linear damping was originally developed more than a century ago and is still of vital interest to physicists, mathematicians and engineers. This theory plays a central role in explaining the stability of many mechanical and electrical systems.

In a mechanical system, for example, a spring may be used as a damping effect to reduce the impact of weight. In an electrical system, a capacitor (C) may be connected to an inductor (L) and a resistor (R), giving rise to an LRC circuit. As a damping effect, improvement methods were prioritized in three somewhat overlapping phases, namely—immediate, refinement and perfection (the art of the possible) for the C-130 PDM team.

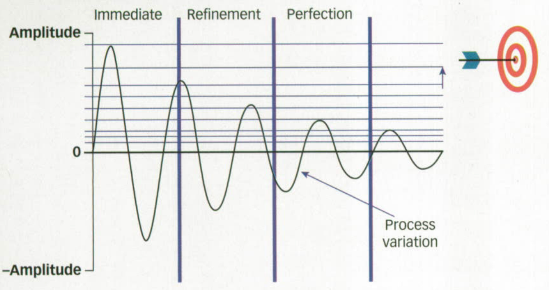
The immediate actions were based on TOC principles. The refinement actions centered on lean concepts, and the perfection actions relied on Six Sigma or more complicated procedures. The idea was to control the release of work, focus on improving efficiencies and fine tune the process.

Performance / TABLE 1

Performance	2010	2011	2012
Due-date performance (percentage)	43.86%	61.31%	98.41%
PDM WIP (number of aircraft)	51	36	16
Dock flow days (calendar days)	102	69	40
Customer reported defects (number per aircraft)	1	0.75	0.16
Throughput (number of aircraft per week)	1	1.26	1.30

PDM = programmed depot maintence
WIP = work in process

The squiggly line / FIGURE 1

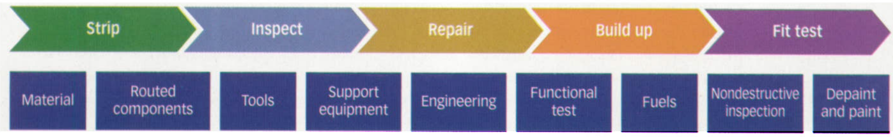


The PDM process

Many U.S. Air Force aircraft undergo PDM. Depot maintenance involves challenging work—such as extensive aircraft disassembly—that is not performed at the field installations. Instead, it occurs at specialized facilities such as the WR-ALC. The word "programmed" refers to maintenance that occurs on a schedule rather than in response to a specific aircraft's condition. Intermittent PDM is established and is essential to keeping a C-130 aircraft operating safely and effectively.

In other words, PDM, or preventive maintenance, increases capability by extending the

C-130 programmed depot maintenance process / FIGURE 2



aircraft's life. The C-130 PDM process is performed in several buildings at the WR-ALC and consists of five major steps, as shown in Figure 2.

1. **Strip.** After removing the fuel from the aircraft (defueling), the aircraft is stripped of most of its components, including engines, flight controls, thrust reversers, ramps, doors and panels.
2. **Inspect.** This includes a detailed inspection of corrosion, cracks or high-stress areas.
3. **Repair.** Most of the repair activities are performed.
4. **Build up.** This includes putting the aircraft back together, reinstalling the engines, flight controls, thrust reversers, ramps, doors and panels.
5. **Fit test.** "Green runs" are performed on the aircraft's engines and flight controls, which are operated while the aircraft is still on the ground. The aircraft begins functional tests and a functional check flight.

After the successful completion of this last step, the aircraft is placed back into service.

The challenge

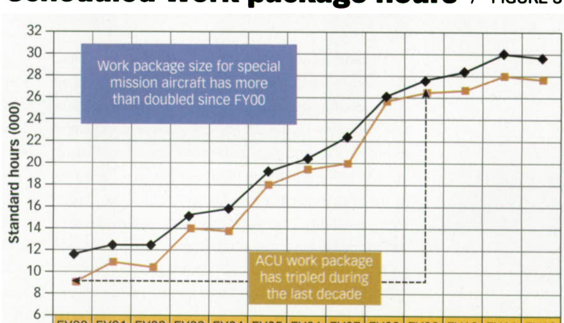
For more than a decade, C-130 aircrafts have experienced significant increases in use rates and intensity of critical mission requirements in multiple theaters of operation. It is, therefore, not surprising that PDM requirements have increased significantly, and weapon systems related to PDM in the Aircraft H model (ACH) and Aircraft U model (ACU) package hours have nearly tripled during the same period.

The intensity of critical mission requirements places tremendous stress on the need to sustain the availability of C-130 aircrafts, which hinges, in part, on the ability of the C-130 PDM team to sustain or reduce flow days in the face of escalating inspection and repair requirements (see Figure 3).

In 2010, the total number of C-130 WIP was 51, and 15 of those aircrafts were queued for the strip or repair steps. The C-130 PDM team's meeting due-date performance stood at a dismal 43.86%, and flow days totaled 102, which was too many. Resources were spread thin across the C-130 PDM to cover the excess WIP on multiple shifts in multiple facilities. To complicate matters, there were far too many changes or modifications to be incorporated into the C-130 aircrafts.

For example, intensive planning was underway for the new C-130J Super Hercules, which would affect the C-130 PDM within a few months. These challenges directly affected the availability of the C-130 aircraft fleet to fulfill critical aircraft mission requirements in multiple theaters of operation.

Scheduled work package hours / FIGURE 3



	FY00	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
ACH	11.7	12.5	12.4	15.3	15.9	19.3	20.5	22.4	26.2	27.6	28.4	30.2	29.8
ACU	9.2	10.9	10.4	14.1	13.9	18	19.5	20.2	25.8	26.7	26.8	28.2	27.8

ACH = Aircraft H model
ACU = Aircraft U model
FY = fiscal year

The squiggly line

The strategic intent of WR-ALC is to be recognized as a world-class performer. Specifically, the strategy articulates the continuous push to reach perfection by setting aggressive targets for quality, cost, safety and delivery improvements. For example, WR-ALC intends to improve delivery, or reduce flow days of aircraft by 20% every year while maintaining 100% on-time performance.

In doing so repeatedly, the strategy is to generate capacity and bring in additional future work—possibly guaranteeing the long-term survival of WR-ALC. Keeping that strategy in mind, C-130 leadership developed a list of significant problem areas for the PDM process.

To address these problem areas, leadership prioritized the improvement methods into the three phases: The immediate phase was based on TOC principles, the refinement phase centered on lean concepts, and the perfection phase relied on Six Sigma or other more complicated approaches.

Phase one: immediate

In TOC, it is acknowledged that all systems have constraints (bottlenecks), and the system's throughput is dictated by the processing capability of the bottleneck. Releasing more work than the process capability of the bottleneck sets in motion a vicious cycle of events, giving rise to high oscillations. As the system's WIP increases, the production floor becomes cluttered, resources are stretched thin and throughput begins to suffer.

As more work continues to be released, the system is inundated with WIP, and production expands to other areas to accommodate the WIP. This puts enormous pressure on the already-stretched resources, and throughput suffers even more. Over time, the situation often worsens, and the amplitude of the cycle increases as the system experiences higher oscillations, resulting in instability. One way to dampen or slow the high oscillations is to control the release of work and focus on WIP reduction and effectively using resources.

Initially, there was little or no control on the release of work to the C-130 PDM process. As a result, overtime was needed, and WIP relating to C-130 aircraft was spread across 10 docks, with additional aircraft queued in various stages of disassembly and reassembly. These docks were physically located in four different facilities, spread across more than one mile in the WR-ALC. This resulted in little or no synchronization of PDM activities.

There were considerable shortages of key resources such as equipment, tools and materials. The aircraft tail teams, which consist of representatives from production, planning, scheduling and material control, were pulled in different directions. The teams experienced difficulty in working closely together and struggled to establish effective communication and cooperation.

C-130 leadership made a bold decision to control the release of workload and reduce WIP of PDMs to six docks. This reduction mitigated the impact of shortfalls in key resources, resulting in improved synchronization of PDM activities. The aircraft tail teams began to work more closely together and improved communication and cooperation. Over time, the teams defined standard roles and responsibilities and worked aggressively to improve C-130 PDM performance on a shift-by-shift, tail-by-tail basis.

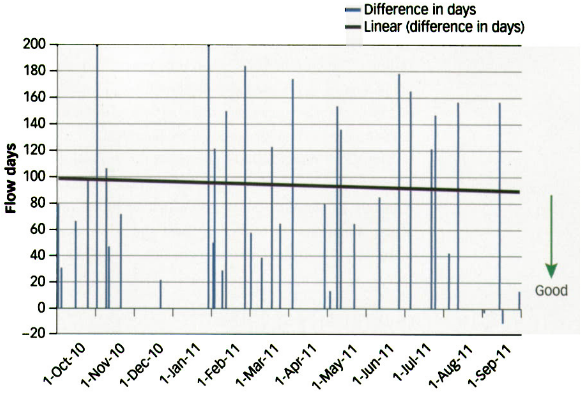
To improve productivity as the aircraft tail teams worked more closely together, the C-130 PDM direct labor workforce was reorganized into dedicated crews to create a sense of ownership. Several dedicated crews were developed by skill or function:

- Disassembly crews prepared the aircraft for paint removal and dock entry.
- Dock crews accomplished inspections, repairs and reassembly.
- Rainbow fitting crews completed inspection, repair or replacement of crucial wing joint components.
- Structural repair crews completed specific complex repairs to major aircraft structures.
- Post-dock crews, which consist of dedicated avionics technicians, focused on conducting outgoing checks prior to functional testing.
- On-site metal bond crews inspected and installed specialized composite repairs (for example, boron and graphite).

This reorganization enhanced focus and effectiveness, resulting in improved yield. Additionally, the workforce experienced increased job satisfaction and more continuity of operations across shifts. The sense of ownership increased as crew members built mutual trust and worked together to their full potential. Ultimately, the increased productivity translated to increased levels of compliance with quality and safety standards and increased throughput as demonstrated by due-date performance gains.

By controlling work release, focusing on reducing WIP and gaining resource concentration, there was a steady increase of throughput and due-date performance. As the C-130 PDM cleared excess WIP, PDM flow days began to drop steadily, falling from 102 in October fiscal 2010 to 79 days in October fiscal 2011. These additional days provided for improved agility to respond, reduced reaction time, and enhanced the close air support and other airlift missions for which the C-130 aircraft is uniquely capable (see Figure 4).

PDM flowdays trend / FIGURE 4



PDM = programmed depot maintenance

Phase two: refinement

As the high oscillations were reduced to moderate levels, lean principles were applied to the C-130 PDM to reduce or eliminate all forms of waste. Traditionally, there are seven categories of waste: overproduction, inventory, defects, motion, processing, waiting and transportation. It requires a great deal of contrived pursuit to identify waste, which sometimes can either be obscure or obvious.

The C-130 production improvement applied lean principles to reduce or eliminate waste from all the steps of the PDM process and its supporting functions. Initially, C-130 leadership identified several problem areas and improvement opportunities throughout the PDM process. The top three high-priority improvement opportunities were:

1. Consolidation of facilities.
2. Use of the space in existing facilities.
3. Major changes to the supporting processes.

Initially, C-130 PDM activities were performed in four different facilities spread across more than one mile in the WR-ALC. As the focus shifted to reducing WIP and increasing throughput, the C-130 PDM team was able to reduce the number of facilities required to perform maintenance by 50%, completely vacating two facilities (buildings 83 and 2316), and freeing 112,300 square feet of covered maintenance floor space to support other workloads.

By eliminating the use of building 2316, the distance of associated aircraft tows from other facilities was reduced by more than one mile. By vacating building 83, sufficient facility space was created for simultaneous work on two additional C-17 aircraft, generating 140,000 work hours and $15.4 million in revenue.

Within the remaining facilities, the C-130 PDM concentrated on space use, shop-floor organization, housekeeping (to maximize control), regulatory compliance and facilitating efficient aircraft maintenance. The six-dock configuration was reorganized using lean principles, such as 6S (sort, straighten, shine, standardize, sustain and safety).

Establishing dedicated storage locations for toolboxes and specialized equipment dramatically reduced clutter around docked aircraft and facilitated maintenance stand repositioning. The facility floors were repainted to improve detection of potential foreign object debris (FOD) and to improve employee working conditions. Typically, FOD consists of nuts or bolts which, if sucked into an aircraft engine, can result in a fatal accident.

These initiatives improved floor space use for the C-130 PDM, clearly increased safety and flexibility, reduced FOD and improved aircraft access. In addition to the floor changes, the administrative offices were reorganized to a day-shift team to provide dedicated office space and a swing-shift team to support the six-dock configuration. This initiative enhanced first-line supervisor oversight of shop floor actions, while also increasing coordination when addressing tactical issues.

The C-130 PDM implemented a host of changes aimed at streamlining support processes. One of the most important changes was the implementation of the maintenance requirements supportability process (MRSP). The core of MRSP logic was designed to enhance supportability through collaboration of WR-ALC, and its back-shop support activities, as well as Defense Logistics Agency and Air Force Global Logistics.

The MRSP functionalities addressed the full scope of activities connected with the C-130 PDM, creating a library of master operations, which included resource requirements (material, tools and hazardous materials). The C-130 PDM's intense focus on deploying MRSP during the second half of fiscal 2011 directly influenced daily maintenance activities. For example:

- Development of trigger packages for recurring repairs.
- Initiation of advance planning for phase two findings to avoid schedule delays due to latent defects.
- Structured preparation of operational workbooks that detail all maintenance requirements for each tail number.
- Induction meetings organized for optimum communication of those requirements.
- Structured business processes for documenting and collaborating logistics system process change requests.
- Ongoing validation of material inventory center local stock quantities.
- Application of dedicated resources to accomplish advance planning of urgent PDM requirements for U.S. Coast Guard C-130 aircraft.

THE C-130 HERCULES

Lockheed Martin's C-130 Hercules primarily performs tactical airlift missions. The C-130 operates throughout the U.S. Air Force, serving with Air Mobility Command, Air Force Special Operations Command, Air Combat Command, U.S. Air Forces in Europe, Pacific Air Forces, the Air National Guard and the Air Force Reserve Command.

The aircraft fulfills a wide range of operational missions in peace and war situations. It can operate from rough dirt strips and is the prime mode of transport for airdropping troops and equipment into hostile areas. Basic and specialized versions of the aircraft perform diverse roles, including: airlift support, Antarctic resupply, aero medical missions, weather reconnaissance, aerial spray missions, firefighting duties for the U.S. Forest Service and natural disaster relief missions.

The C-130 aircraft's role in executing military missions cannot be overstated. As the backbone of the Air Force's airlift capability, these aircrafts are absolutely crucial in providing supplies and positioning troops. The C-130 also provides close air support and an array of special mission capabilities to U.S. warfighters on the ground in Operation Enduring Freedom and Operation New Dawn in Afghanistan.

In addition, the C-130s are consistently relied on throughout the world for humanitarian missions, medical and resupply support, and repatriation details. Most recently, C-130s were pivotal in supporting refugees in Libya and Tunisia, earthquake victims in Turkey and tsunami victims in Japan. C-130s also played an important role in many rescue operations in New York and New Jersey following the Hurricane Sandy devastation. —*S.S.C.*

Phase three: art of the possible

As moderate oscillations were reduced to low levels, the C-130 PDM team applied Six Sigma or other more complicated approaches.

In the C-130 PDM, Six Sigma incorporated complicated procedures for tending to the challenging repair requirements on numerous C-130 aircrafts. Working closely with engineers responsible for weapon system sustainment requirements, the C-130 PDM team identified exceptional defects and implemented complex repairs to restore aircraft structural integrity.

In addition, complex changes to the C-130 PDM to improve the performance of the C-130 also were implemented. Examples of complex repairs and a complex process include:

Repairing flawed holes in the lower forward spar on the C-130 ACH. Nondestructive inspections revealed that at the fuselage station (FS), the main landing gear FS 517 beam had cracks that had to be repaired in critical fastener locations. Due to the location of the holes, using normal procedures to correct the damage would compromise minimum edge distance requirements (that is, extending too close to the radius).

Based on detailed engineering guidance, the C-130 PDM team took extraordinary steps to complete the repairs. The process began with the stripping of the left inboard cavity in the left auxiliary fuel tank, removing the center wing box (CWB) attach angle (about 11

The perfection **(art of the possible) actions** relied on **Six Sigma or more complicated approaches.**

feet long), removing the inboard and outboard drain trough, removing the gear box located directly to the left of the FS 517 beam, and cutting and trimming the left auxiliary tank and dry bay so the repair inside the auxiliary tank would fit.

The C-130 PDM team removed, inspected and reamed holes to oversize dimensions to accommodate fasteners common to the CWB attach angle that extended through the wing plank, FS 517 beam, web and the tapered titanium doublers. The CWB attach angle had to be routed to a back-shop activity for specialized machining services to mill out the location of the titanium doublers under the CWB attach angle. This level of structural disassembly, modification and reassembly required unusually complex maintenance work to return this aircraft to airworthiness for the warfighter.

Work on the C-130 ACH related to aging aircraft issues. Characteristically replete with aging aircraft issues, such as cracks and corrosion, this model was no exception. It required extensive composite doubler repairs and specialized repairs of flawed holes, as well as repairs of cracks in two paratroop door frames. Compounding these challenges was the replacement of the cargo ramp that had been cannibalized earlier from this aircraft to support the mission of another aircraft.

Initially, seeking support from the exchangeable repair line, the C-130 PDM team discovered no ramps were available through the standard supply chain. C-130 leadership located a potentially acceptable cargo ramp at one of the field installations after days of exhaustive search of different databases.

The cargo ramp was photographed in the field, and digital photos were painstakingly examined to determine the suitability of repair requirements. After suitability was determined, the cargo ramp was shipped to WR-ALC. On arrival, the cargo ramp was thoroughly inspected, repaired and installed on the aircraft as it proceeded through the remainder of the PDM processes.

Four fixed release controls (FRC) were implemented at strategic points in the C-130 PDM. This implementation was difficult but necessary to continue to improve the due date performance of the C-130 PDM. C-130 leadership staggered four gates in the entire C-130 PDM process (120 flow days) considering major jobs or change in scope.

The predock FRC was located after 20 days and the inspection FRC was created after 20 days. At this point, two orders were placed (full kits one and two) for all the parts and components (for example, flight controls) needed for the repair and buildup of an aircraft. The repair and build FRC was placed after 40 days in dock, and finally, the postdock FRC was positioned after 40 days.

Additional controls or milestones also were established within each FRC to enforce completion of major jobs to avoid overcommitment of resources that could possibly reduce throughput. Each FRC had a complete list of items that needed to be completed and verified by the appropriate authority before allowing an aircraft to go through the FRC. Implementation of FRCs improved due date performance and instilled quality through intermediate process discipline, while ensuring higher performance for support agencies.

Lessons learned

There is widespread confusion in organizations attempting to select a particular improvement method for their business environment. The difficulty is that there are as many TOC zealots as there are lean and Six Sigma fanatics. There is a natural propensity for some organizations to choose one method over the other, and often a change in leadership triggers a change in method.

To produce exceptional results, you must prioritize improvement methods or optimally mix them. **QP**

REFERENCE

1. H.G. Wells, *The Time Machine*, William Heinemann, 1895.

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